AQUIFER STORAGE RECOVERY
IN COASTAL PLAIN SEDIMENTS
AT MYRTLE BEACH, SOUTH CAROLINA

By

Joffre Castro

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The Myrtle Beach ASR Project is a cooperative effort of State, Local Governments, and Municipalities under the direction of the CH2M Hill in coordination with the Water Resources Commission.

ABSTRACT

The rapid growth and economic development of the city of Myrtle Beach and surrounding areas have subjected the Black Creek aquifers to large ground-water withdrawals. Increased water demands have stressed the hydrological system to the point that dewatering of the aquifers probably will occur by the year 1990. One solution to this problem, known as Aquifer Storage Recovery (ASR), is currently being investigated.

A surface-water treatment plant on the Atlantic Intracoastal Waterway (AICW) is under construction in Myrtle Beach. At this site two ASR strategies might be feasible. Treated surface water from the plant could be injected into the aquifers of the Black Creek Formation or into the nonpotable aquifers of the Middendorf Formation. The surplus treated water would be stored during the winter months, to counter the declining water levels and to reduce the potential for saltwater intrusion, and it would be recovered in the peak water-demand season during the summer.

The objective of this project is to study and determine the feasibility of utilizing Black Creek and Middendorf aquifers for the injection, storage, and recovery of potable water. The investigation will focus on identifying pretreatment methods to prevent clay dispersion, clay swelling, and undesirable chemical precipitations resulting from the mixing of treated surface water with the native formation water.

The general approach involves obtaining core samples from the potential storage zones, running column tests to determine the effectiveness of pretreatment methods, performing chemical balance and solute-transport computer simulations, and constructing a prototype ASR well.

INTRODUCTION

The present water supply for the city of Myrtle Beach, South Carolina, (Fig. 1) is obtained almost entirely from aquifers in the Black Creek Formation. Water demand increases by a factor of 1.7 during the summer months as a result of the large tourist industry generated by the beaches. In the vicinity of Myrtle Beach, the potentiometric surfaces of these aquifers are declining at rates as great as 10 feet per year due to increased pumping resulting from the continued growth and development. At this rate, the aquifers of the Black Creek Formation will begin to be dewatered by 1990. In addition, ground-water withdrawal in this area has reversed the natural seaward hydraulic gradient, thereby increasing the potential for saltwater intrusion.

A solution to this problem is currently under investigation. This alternative involves the Aquifer Storage and Recovery (ASR) concept, which is the cyclical storage and retrieval of surplus treated drinking water. Two ASR strategies may be feasible in the solution of this problem.

A surface-water treatment plant on the Atlantic Intracoastal Waterway (AICW) is currently under construction in Myrtle Beach. At this location, either alternative may be feasible. The first strategy involves injecting surplus treated freshwater from the AICW plant into the Black Creek aquifers during the winter months in order to counter the declining water levels and to reduce the potential for saltwater intrusion. In the second strategy, the surplus freshwater is stored in the nonpotable aquifers of the Middendorf Formation. In both strategies, the stored water is recovered in the peak water demand-period during the following summer.

The concept of aquifer recharge has been studied in great detail, and three international symposia have been held that demonstrate the worldwide scope of interest in the topic (Israel, 1967; England, 1970; and New Orleans, 1973). Numerous approaches have been tried, with various degrees of success, using water supply sources ranging from very highly treated water and wastewater to untreated runoff collected from lakes and ditches. There have been many reasons cited for the use of artificial recharge of aquifers, including replenishing local overdrafts, reducing the threat of saltwater intrusion, storing surplus water, augmenting freshwater supplies, improving resident water quality, and controlling land-surface subsidence.

There are at least two nations with currently operational ASR projects; the United States with four and Israel with an undisclosed number. The four ASR systems in the United States are: the Goleta Water District in southern California; Wildwood, N. J.; Manatee County, FL.; and Peace River, FL. Most of the operational ASR systems inject water into carbonate aquifers and are, therefore, not directly comparable to the proposed project. Those not involving carbonate aquifers, such as the Wildwood site, are utilizing aquifers with minimal clay content and are not documented.

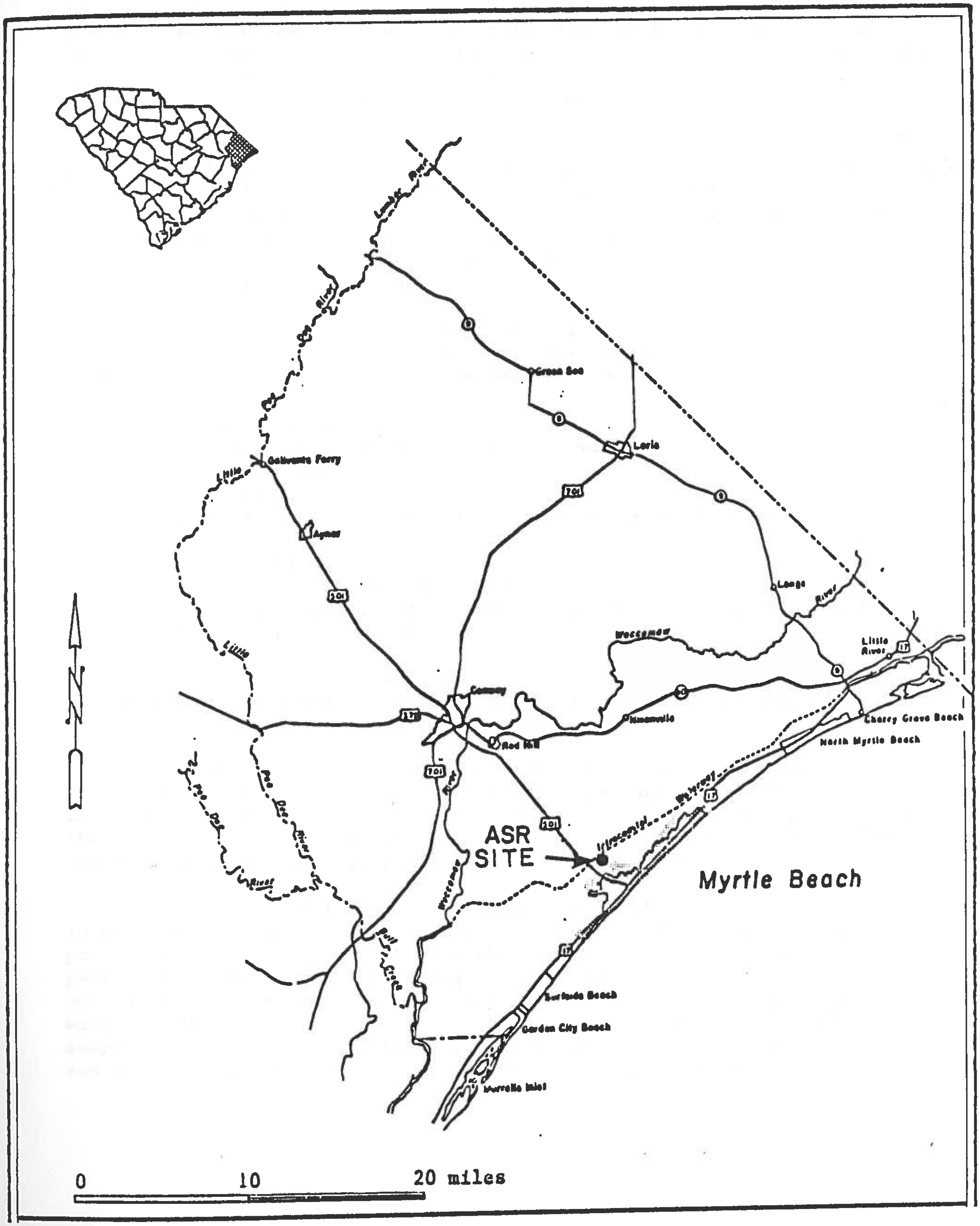

Figure 1. Location of ASR feasibility study area, Myrtle Beach, Horry County, South Carolina.

There have been several unsuccessful attempts to recharge aquifers through injection wells. Two are of particular interest to the present project, because they involved unconsolidated, or poorly consolidated, sand units containing an appreciable clay fraction similar to the aquifers in the Black Creek and Middendorf Formations in coastal South Carolina. The first attempt was at Norfolk, VA., (Brown and Silvey, 1977) where a sand aquifer of Late Cretaceous age was subjected to four cycles of injection and recovery and, as a result, was plagued with clay-dispersion problems. The second attempt was at Bay Park, on Long Island, (Vecchioli, Ku, and Sulam, 1980) where drinking water and tertiary-treated sewage were injected into the Magothy aquifer, of Late Cretaceous age. Between 1968 and 1973 a total of 19 recharge recovery cycles were completed at Bay Park, with reported problems of well clogging due to particulate matter building up on the well screen.

Many operational problems can be involved in an ASR project. Sniegocki (1963) presented the following mechanisms of clogging of recharge wells in the Grand Prairie Region in Arkansas:

1. bacterial growth;
2. suspended material in the injected water;
3. air entrainment;
4. chemical precipitation on the well screen or in the formation;
5. jamming of the aquifer caused by rearrangement of aquifer materials;
6. swelling of formation clays;
7. dispersion of formation clays; and
8. biochemical precipitation caused by iron-reducing bacteria or sulfate-splitting organisms.

Olsthoorn (1982) identified all but the last of the above mechanisms as operational problems encountered in artificial recharge projects in the Netherlands.

During the Bay Park and Norfolk tests, bacterial growth was inhibited by maintaining a chlorine residual in the injected water. If the recharge water is not treated in this manner, the bacteria will form a slime mat on the well screen and in the gravel pack. The slime mat will reduce flows and trap any suspended materials in the injected water.

The presence of only 1 mg/L of suspended solids in the Bay Park injection water caused severe clogging of the injection well. This problem occurs because even though the concentration of suspended particles is low the volumes being injected are large. For example, during the last recharge cycle at Bay Park, 42 million gallons of water were injected, and at 1 mg/L there would have been about 350 pounds of suspended matter placed in the well and formation. This problem can be avoided if proper measures are taken to filter the recharge water.

Air entrainment is generally caused by three factors:

1. cascading of injected water into the well;
2. chemical reactions between injected water and native formation water; and
3. gas solubility changes induced by alteration of the pressure or temperature in the formation.

The entrained gases usually occur as minute bubbles in the intergranular spaces, causing a binding effect in the aquifer and reducing its permeability.

Several methods for preventing air entrainment caused by the first factor have been suggested. These include:

1. injecting the water approximately 12 to 13 feet below the water level in the well (Edworthy and Downing, 1979);
2. fitting the inner injection pipe with an orifice to maintain positive pressure (Sellinger and Aberbach, 1973);
3. using multiple small-diameter injection pipes in large-diameter wells; and
4. preventing air leaks in the system (Olsthoorn, 1982).

The remaining two factors, causing air entrainment, can be at least partially eliminated by proper chemical treatment and by reducing temperature differentials between native and injected water.

Chemical precipitation can occur when water of two different chemistries are combined. Calcium carbonate and iron and magnesium oxides are common precipitates. When these reaction products form on the well screen or in the formation, they can reduce permeability enough to cause a project to be unfeasible.

The reversal of flow directions during injection and recovery cycles can cause aquifer materials to become rearranged into a less permeable structure. For example, mica flakes may become reoriented perpendicular to the flow direction, or sand grains may become repacked into a tighter arrangement.

Clay swelling is a largely reversible process and is caused by a water-quality difference between the native ground water and the recharge water in the presence of a swelling clay such as smectite. When clay particles containing interlayer formation water with a high ionic strength come in contact with water having a low ionic strength, the surrounding water will diffuse into the clay, causing it to swell. It is believed that, in most cases, clay swelling is not an important factor in the reduction of aquifer permeability (Brown and Silvey, 1977).

The most likely problem to be encountered when injecting water into a somewhat clayey aquifer is clay dispersion. This phenomenon is caused by a change in thickness of the double layer of ions surrounding the negatively charged surfaces of the clay particles. In water with a high ionic strength, as found in many depositional environments, the double layer is compressed, and the interparticle van der Waals forces cause the clays to flocculate. When more dilute water comes in contact with the flocculated clay, the double layer expands and the clay particles separate and are put into suspension. When this occurs during injection of freshwater into an aquifer, the clay particles migrate until they become lodged in the aquifer pore channels, thus reducing aquifer permeability. Reinstating the native ground water after the clay has dispersed will not replace the clay to its original position (Brown and Silvey, 1977).

The tendency for clay to disperse can be reduced by replacing large monovalent hydrated ions such as Na^+ with small di- or tri-valent ions such as Ca^{2+} or Al^{3+} in the double layer. In two separate laboratory studies (Jones, 1964; Brown and Silvey, 1977), a calcium chloride pretreatment solution was successful in significantly reducing permeability losses due to clay dispersion. Other pretreatment techniques have been employed by the petroleum industry but have not been applied to potable aquifers.

REQUIREMENTS FOR AN OPERATIONAL ASR SYSTEM

1. A seasonal water use pattern having a peak- to normal- loading ratio of at least 1.5.-- The city of Myrtle Beach, in Horry County, is located in the extreme eastern part of South Carolina (Fig. 1). Although, the region is largely rural with an agricultural economy, the city, an internationally popular resort area, is densely populated and economically supported by summer tourism.

The demand for water along the beach fluctuates in direct response to the changing population (Fig. 2). The municipal population of the city obtains almost all of its drinking-water supply from wells completed in the Black Creek Formation. Table 1 shows that between 1974 and 1984 the ground-water use in Horry County, which reflects the water use in the city of Myrtle Beach, increased by 190 percent. By the year 2000, projected usage will increase an additional 92 percent. The peak demand, which exceeds the average demand by a factor of approximately 1.7, shows the stress to which the aquifers are being subjected during the peak of the tourist season.

2. A source of surplus treated drinking water for use in recharging the aquifers.-- In order to meet its projected water needs through this century, the city of Myrtle Beach is presently constructing a surface-water treatment plant on the Atlantic Intracoastal Waterway (AICW) with a peak capacity of 20 million gallons per day. This plant will replace the large producing wells owned by the city through 2002.

This water treatment plant has been selected as the ideal test site for the ASR project. This site is underlain by potential recharging aquifers, is located in the center of a cyclical-demand area, and has available the treated excess flow of the plant during winter months.

The AICW is a series of linked natural, and man-made, man-improved waterways. It was constructed by the Army Corps of Engineers to facilitate water-borne commerce along the Eastern Seaboard. The AICW extends from New Jersey to Florida as a continuous navigable channel. The section just to the west of the Grand Strand (including the city of Myrtle Beach) is the only stretch containing freshwater.

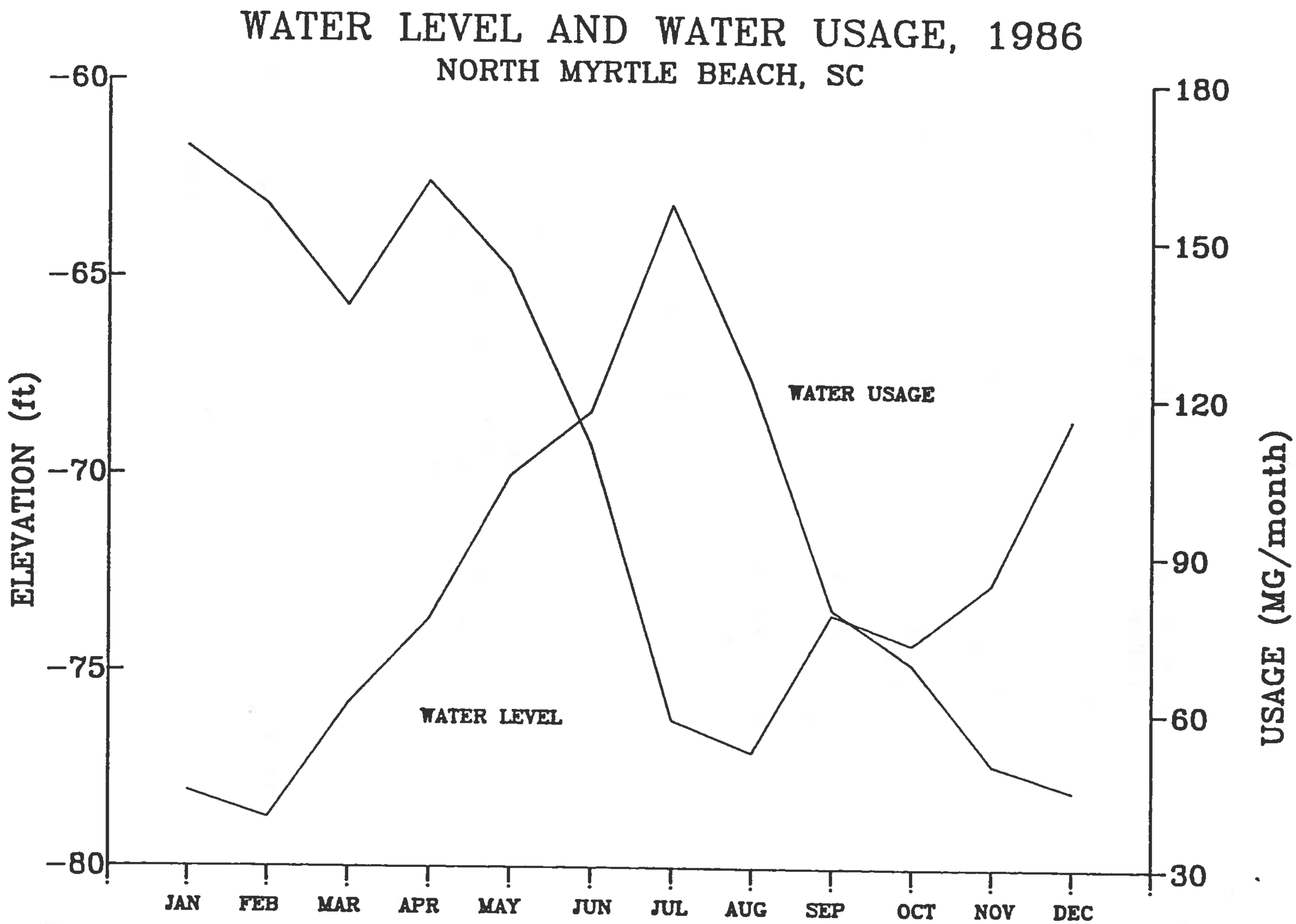

Figure 2. Ground-water level and water usage, North Myrtle Beach, S.C.

Table 1. Water use from the Black Creek Formation

YEAR	WATER USE MG/YEAR	WATER DEMAND MG/DAY
1974[1]	2,780	Average 7.6 Peak 12.7
1982	5,950	Average 16.3 Peak 27.3
1984	7,956	Average 21.8 Peak 32.6
1985	8,081	Average 22.1 Peak 30.6
1986	5,780	Average 15.8 Peak 24.3*
2000[2]	15,500	Average 40 Peak 72

MG/year = million gallons per year;
MG/day = million gallons per day;
Average = million gallons per year divided by 365 days;
Peak = maximum monthly use (MG/Month) divided by number of days in month.

Note: 1986 data have not been verified and are not used in the calculations.

Sources: [1] Zack, 1977;
[2] CH2M HILL, 1984

3. A suitable aquifer.-- The sediments overlying the crystalline bedrock in the region have been classified into four principal geologic units (Fig. 3). They are the Middendorf, Black Creek, and Peedee Formations, and the shallow deposits. Considerable debate has occurred in recent years over formation boundaries and nomenclature, including the presence or absence of the Cape Fear Formation in the area. For the purpose of this study the units are referred to as described by Zack (1977) and Pelletier (1985).

The crystalline bedrock is a pre-Cretaceous metamorphic and igneous rock such as schist, gneiss, basalt, and granite. The top of the bedrock complex dips to the south-southeast, owing to the Cape Fear Arch, a southeastward plunging basement nose.

The Middendorf Formation is a Late Cretaceous unit lying unconformably on the bedrock. It consists of multicolored clay and white or gray coarse sand and gravel. In this area there is little information about aquifers of this unit. Hydraulic conductivity is expected to be equal to or greater than those of surrounding aquifers in the area; the potentiometric surface is expected to be 100 feet above mean sea level; and most wells tapping these aquifers have been reported to yield saline water.

The Black Creek Formation is a Late Cretaceous formation consisting of dark-gray clay interbedded with gray or white fine- to very fine-grained quartz sand, and thin but continuous layers of hard cemented calcareous sandstone. The aquifers in this unit are the principal source of water for wells in the area. Hydraulic conductivity is 220 gpd/ft^2; the potentiometric surface, at the site, is 110 feet below mean sea level; the water is of a sodium bicarbonate type, soft, low in iron, and alkaline but having objectionable concentrations of chloride, fluoride, sodium, and total dissolved solids.

The Peedee Formation is the uppermost Cretaceous unit in the State. It was deposited in an open-shelf environment, and consists of dark-gray, fine-grained clayey sand with zones of coarse and shelly loose limestone. Hydraulic conductivity is less than that of Black Creek; aquifers are in general under artesian conditions and have water of poor quality.

The shallow deposits consist of thin beds of fine clayey sand, fine-grained calcareous sand, and limestone of Tertiary and Quaternary age. Most often these aquifers are discontinuous, subject to large water level fluctuations, and dependent on local rainfall for recharge. The quality of the water is variable and usually inferior to that of deeper aquifers.

Of these five units, the Black Creek and Middendorf aquifers will be studied to determine their individual suitability as potential recharging zones for the ASR project. Preliminary information presented by Castro and Hockensmith (1987) suggests that aquifers of the Middendorf and Black Creek Formations are better targets for the ASR project than those of other units and that the Middendorf aquifers may be the best. The aquifers in the Middendorf Formation appear to be cleaner and made of coarser particles, which means that the aquifers may have greater hydraulic conductivity. The hydrostatic level, at the water-treatment

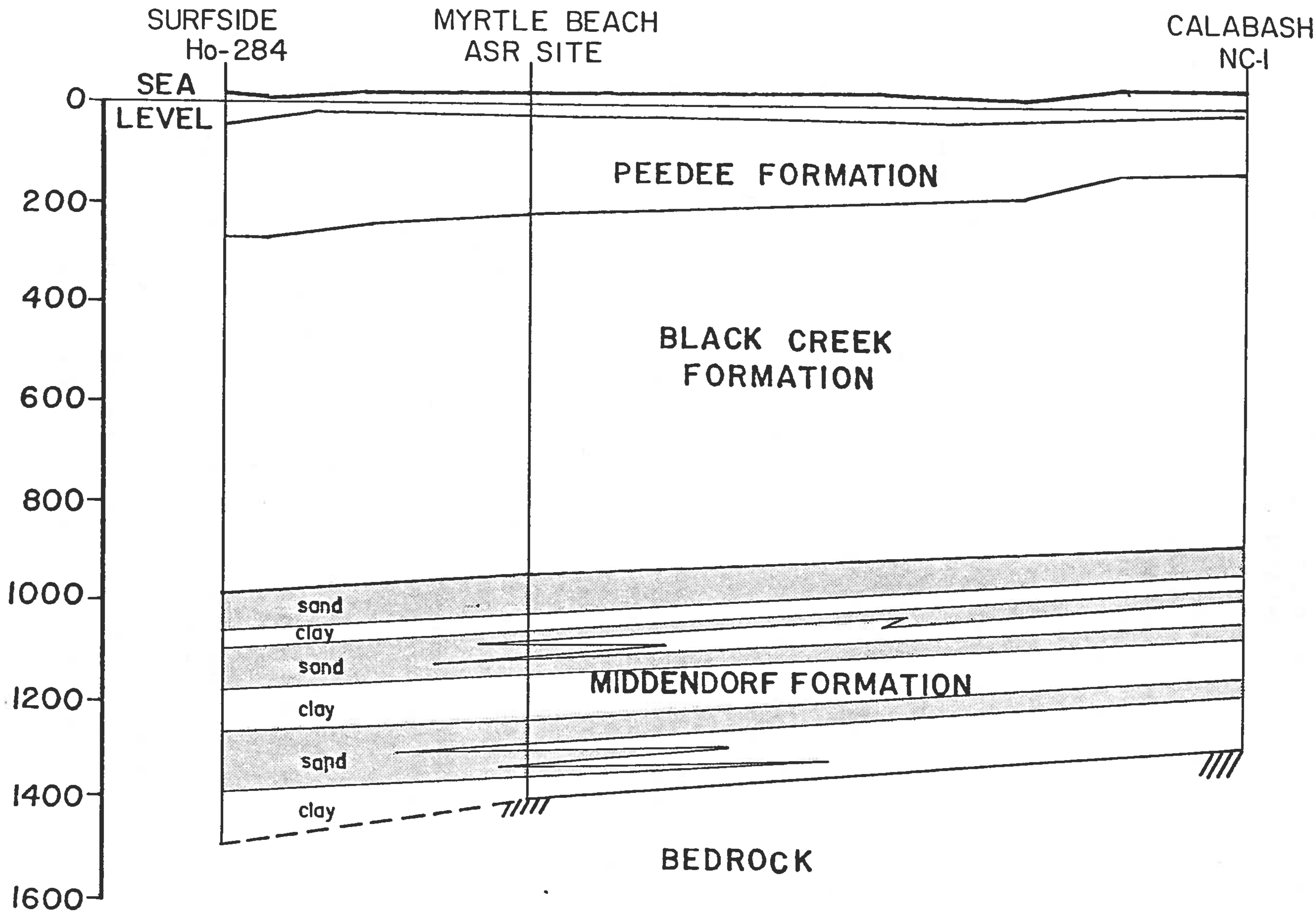

Figure 3. Geologic section from Calabash, N.C., to Surfside, S.C. (after Zack, 1977)

plant site, is estimated to be around 100 feet above land surface; while the hydrostatic level for the Black Creek is 110 below land surface, resulting in a hydrostatic head difference of 210 feet. Thick, continuous clay layers separate these two units, creating two hydraulically independent systems.

Water from the Black Creek aquifers is of a sodium bicarbonate type, soft, low in iron, and alkaline, but it has objectionable concentrations of chloride, fluoride, sodium, and total dissolved solids. Water from the Middendorf aquifers is known to be saline throughout the study area. According to Zack (1977), the saline water is unflushed dilute connate water.

OBJECTIVES

The primary objective of this study is to determine the suitability of several aquifers in the Black Creek and Middendorf Formations for the injection, storage, and recovery of treated surface water from the AICW plant. This investigation would focus mainly on solving the potential problems of clay swelling, clay dispersion, and chemical precipitation. In order to achieve the objectives, the following tasks have been designed:

Task 1.-- Obtain cores from the targeted potential storage zones, and make initial analyses of grain-size distribution, porosity, and mineralogy.

Task 2.-- Measure the hydraulic conductivities of the potential storage zones, and determine head differences between these zones. Hydraulic conductivities and head differences will be measured by installing in the test hole temporary screens located in zones from which the cores were obtained. Hydraulic conductivities will also be measured in the core samples in the laboratory.

Task 3.-- Determine the native ground-water quality in the targeted zones, using standard laboratory and field techniques.

Task 4.-- Determine the quality of the treated water from the proposed surface- water treatment plant on the AICW, using standard laboratory techniques.

Task 5.-- Determine, in the laboratory, the chemical and physical changes caused by flushing the treated surface water through core samples saturated with native ground water. The specific phenomena to be monitored include:

1. water chemistry changes, including the formation of precipitates and the dissolution of aquifer constituents.

2. alteration of aquifer mineralogy and structure, as determined by X-ray diffraction and microscopic analysis.

3. changes in permeability and porosity of the cores.

Task 6.-- If clay dispersion and/or chemical precipitation significantly reduce the permeability of the cores, perform laboratory tests on additional core samples to determine the effectiveness of several environmentally sound and economically feasible pretreatment methods for preventing or reducing the magnitude of the problems.

Task 7.-- Using data gathered in Tasks 1 through 6, implement a numerical model to make a preliminary estimate of the volume of water of a given quality that may be recovered for a number of injection, storage, and recovery schemes. If conditions appear favorable, the numerical simulations will be later verified and the model further calibrated after conducting an actual pilot-scale test.

Task 8.-- After necessary field tests have been performed on the test hole it will be converted into an injection well. Several injection, storage, and recovery schemes will be tried, reflecting results obtained from the laboratory and field tests.

METHODOLOGY

Task 1: Acquisition of Core Samples and Initial Analysis.-- An 8-inch diameter test hole will be drilled through the Black Creek and Middendorf Formations. Undisturbed, 2.3- to 3.5-inch cores will be obtained within preselected intervals, using a core barrel with a nonrotating, removable, transparent inner sleeve. Continuous cores will be obtained throughout the Middendorf Formation. Before tests are performed on the cores, a representative sample of each will be analyzed for grain size, porosity, and mineralogy. Sieve analyses will be used to determine grain-size distributions. Standard weighing techniques will be used to calculate porosities. Non-clay mineralogy will be determined under the microscope, while clay mineralogy will be evaluated by X-ray diffraction. The remainder of the cores will be sealed for later analyses.

Task 2: Measurement of Hydraulic Properties.-- Temporary well screens will be placed opposite the targeted storage zones in the test hole to measure hydraulic conductivities and head differentials. Heads will be measured by pressure transducers located in the temporary well, and hydraulic conductivities will be calculated from data gathered during pumping tests. It is anticipated that a minimum of three zones will be tested in this fashion. Hydraulic conductivities will also be calculated from data gathered in a series of laboratory permeameter tests under tasks 5 and 6.

Task 3: Determination of Native Ground-Water Quality.-- During the pumping tests, four ground-water samples will be collected from each discrete zone: a raw sample, an acidified sample, a filtered sample, and a filtered-acidified sample. In addition, samples from at least three wells, for which adequate construction documentation is available and which provide north-to-south coverage of the study area, will be analyzed to provide representative water quality data for the Black Creek aquifers. Concentrations of chemical constituents will be compared with tabulated data from other wells in the study area in order to determine their inherent degree of variability. A large representative sample of native water, to be used in column tests under Tasks 5 and 6, will be collected from each zone.

Using standard procedures, samples will be analyzed for primary and secondary drinking water standards as well as other parameters important in ASR research (Table 2).

Task 4: Determination of Injected Water Quality.-- A representative large-volume sample of raw water from the AICW will be obtained. Surface-water treatment processes will be duplicated in the laboratory to produce a large-volume sample of treated water that is representative of the quality expected from the proposed treatment plant. This water will then be analyzed for the constituents listed in Table 2. The raw-water sample would be obtained between October and May, those months of the year when well-field recharge activity would normally occur.

Task 5: Determination of Chemical and Physical Changes Caused by Introduction of Treated Surface Water into the Aquifers.-- For each sampled interval, an experiment will be conducted by using two samples obtained in Task 1. Both samples will contain essentially identical material, will be placed in permeameter columns, and will be initially saturated with native ground water. Native ground water and treated surface water will be cyclically passed through the first column, and native ground water alone will be passed through the second column, duplicating the pumping scheme of the first column. During each cycle, permeability will be calculated from the pressure differentials and flow rates.

Each cycle will continue until the permeability stabilizes. During each cycle, samples will be collected from the discharge and analyzed for turbidity, sodium, calcium, and clay content (if turbid). At the end of a predetermined number of cycles, the non-clay mineralogy of the two core samples will be examined under the microscope; X-ray diffraction will be used to determine clay mineralogy and morphology, and porosity will be calculated by standard weighing techniques.

A separate test of the reaction of native and treated water, in the absence of aquifer materials, will also be conducted. On the basis of the above analyses, chemical reactions will be deduced. In addition, theoretical reactions will be explored.

Task 6: Testing of Pretreatment Methods.-- For each sampled interval, laboratory column tests will be performed to test the effectiveness of certain methods for pretreating the aquifer to stabilize the clay in the sediments and/or to prevent chemical precipitation. In concurrence with State and Federal regulatory agencies, three pretreatment alternatives will be selected and prioritized as to desirability for use in a potable aquifer. Previous laboratory studies (Brown and Silvey, 1977; Jones, 1964) found that a calcium chloride solution was successful in significantly reducing clay dispersion; therefore, it is tentatively planned to test this pretreatment method, as well as other compounds such as potassium salts and hydroxy aluminum of: chloride, iodide, nitrate, and sulfate. The procedure will use columns with essentially identical formation samples. They will be first saturated with native water, then pretreated with one of the selected options, and then flushed with treated surface water. Additional cycles of native water, followed by treated surface water, will be run to test the permanence of the pretreatment techniques.

Table 2. Water Quality Characteristics

A. PRIMARY DRINKING-WATER LIST:

Inorganic chemicals:

Arsenic	Mercury
Barium	Nitrate
Cadmium	Selenium
Chromium	Silver
Lead	Fluoride

Organic chemicals:
Trihalomethane

Turbidity

Microbiologic contaminants

B. SECONDARY DRINKING-WATER LIST:

Chloride	Manganese
Color	pH
Copper	Sulfate
Corrosivity	Total Dissolved Solids
Hydrogen-sulfide	Zinc
Iron	

C. OTHERS:

Alkalinity	Dissolved oxygen
Calcium	Magnesium
Carbonate-hardness	Temperature
Conductivity	Total hardness
Density	Total organic carbon

The above procedure will be refined as necessary to match the availability of core material with the number of pretreatment alternatives required. The most desirable alternative will be tested first. A decision regarding subsequent testing of the other alternatives versus further testing of the first alternative will be deferred until initial testing is completed. During the column tests, changes in permeability will be calculated from the measured pressure differentials and flow rates.

After column testing, the cores will be analyzed under the microscope to determine the non-clay mineralogy. X-ray diffraction will be used to determine the clay mineralogy and any changes in clay morphology. In addition, porosities will be calculated by standard weighing techniques in order to determine if any changes have occurred.

Task 7: Numerical Simulation:-- After completing Tasks 1 through 6, sufficient data should be available to conduct a preliminary numerical simulation for the proposed ASR site. This simulation will provide a range of estimates for the volume of water of a given quality that would be recovered for specific injection-storage- recovery schemes. In addition, the simulation will estimate the effect of the project on the existing potentiometric surfaces for the aquifers in question. After final calibration, the model will be used for well-field design and evaluation of best- management practices.

Task 8: Prototype ASR well.-- Subsequent to calibration and verification of the numerical model, and if the results of this study indicate the suitability of the aquifers, a prototype injection, storage, and recovery test well will be constructed from the test hole.

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